

Passive Shielding in CUORE

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*on behalf of the
CUORE Collaboration*



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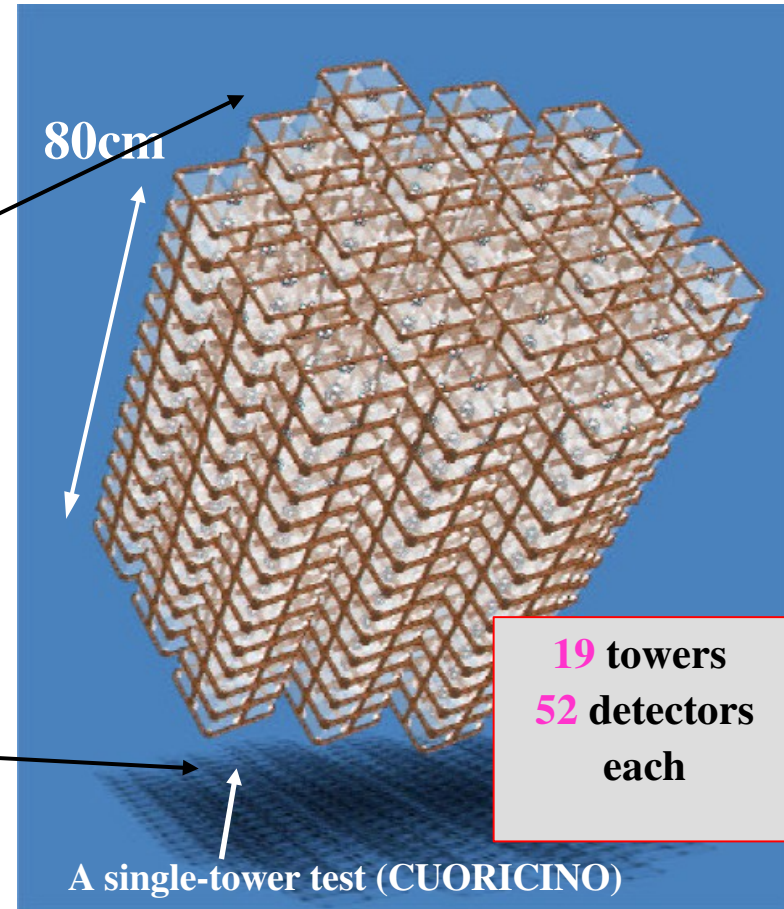
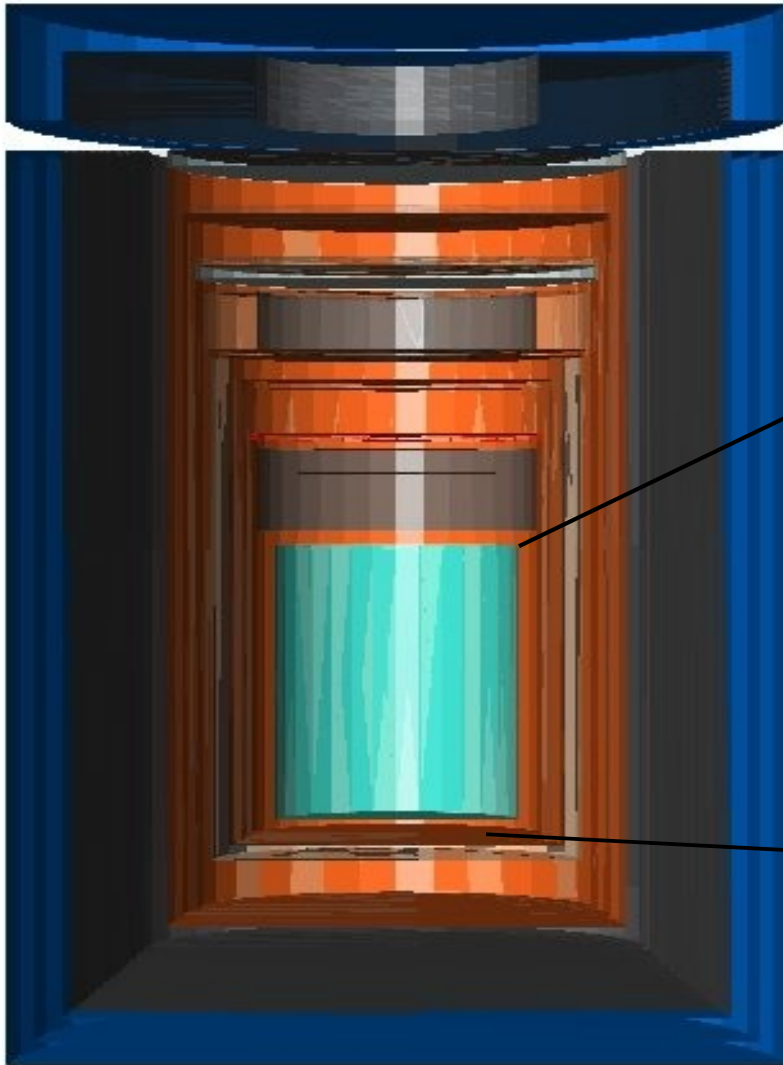
Cryogenic Underground Observatory



Single dilution refrigerator ~10 mk

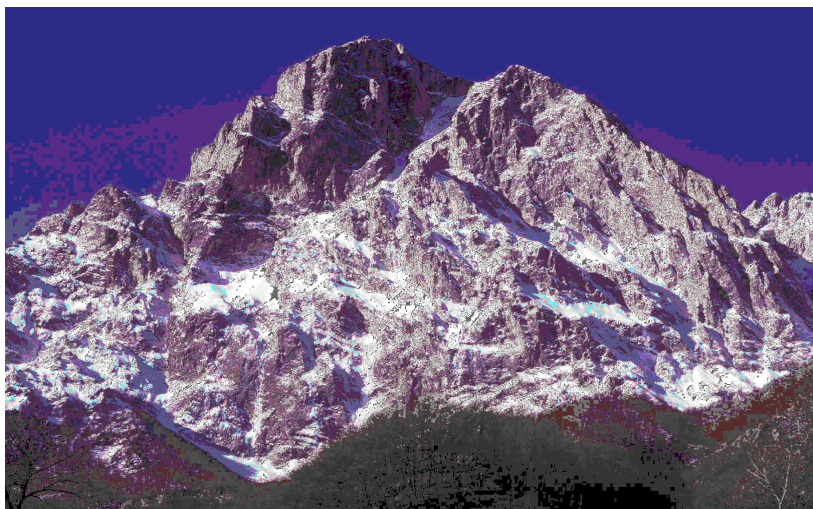
for Rare Events

- $\beta\beta 0\nu$, Cold Dark Matter searches
proposal hep/ph 0501010



Closed packed array of 988 TeO₂ 5x5x5 cm³ crystals $\Rightarrow$ 741 kg TeO₂ $\Rightarrow$ 204kg ¹³⁰Te

CUOR(ICINO) @ LNGS



Cuoricino experiment is installed in the

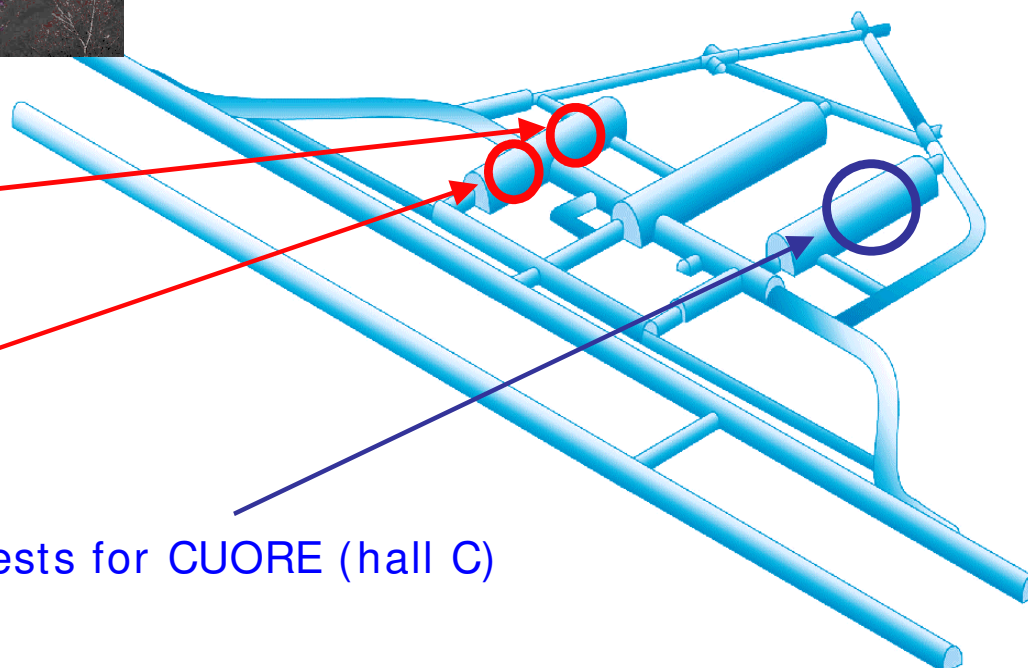
**Underground National Laboratory
of Gran Sasso
L'Aquila – ITALY**

the mountain providing a **3500 m.w.e.
shield** against cosmic rays

CUORE
(hall A)

Cuoricino

R&D final tests for CUORE (hall C)



Background challenge

CUORE $\beta\beta 0\nu$ sensitivity will depend strongly on the **bkg level** and **detector performance**

mass, efficiency & resolution almost fixed
sensitivity depends on **T** and **background**

$$S^{\beta\beta 0\nu} \propto a \cdot \epsilon \cdot \left(\frac{MT}{\Gamma b} \right)^{1/2}$$

detector mass [kg] • measuring time [y]

energy resolution[keV] • bkg [counts/keV/kg/y]

isotopic abundance • detector efficiency

In 5 years of data taking

CUORE GOAL:
test inverse hierarchy: **19-50 meV**

b(c/keV/kg/y)	Γ (keV)	$T_{1/2}^{0\nu}$ (y)	$ \langle m_\nu \rangle $ (meV)
0,01	10	$1,5 \times 10^{26}$	23 - 118
0,01	5	$2,1 \times 10^{26}$	19 - 100
0,001	10	$4,6 \times 10^{26}$	13 - 67
0,001	5	$6,5 \times 10^{26}$	11 - 57

Background reduction



BKG SOURCES

- Radioactive contaminations in the detector materials, on the detector surfaces
- Radioactive contaminations of the set-up – shielding included
- Neutrons
- Muon induced neutrons

THE SOLUTION

- Select **construction materials** according to their contamination (ICPMS, n-activation, HPGe)
- Avoid **contaminated materials** (use Cu, Pb and TeO_2 where you can)
- Avoid **activation** (cosmogenic isotopes -> reduce exposure above grounds)
- Build thick efficient **gamma** and **neutron shields**
- Build (eventually) a muon veto to tag **muon-induced neutrons**

CUORE background prediction based on
Cuoricino experience – Cuoricino bkg model
+ specific measurement with a dedicated detector (**RAD – HallC**)

Cuoricino: 0.18 ± 0.01 counts/keV/kg/y

→ **70%** interpreted as **surface bkg**
30 % ^{208}Tl from ^{232}Th in *cryostat shield*

hall C: $< 2.5\text{-}3 \cdot 10^{-2}$ counts/keV/kg/y

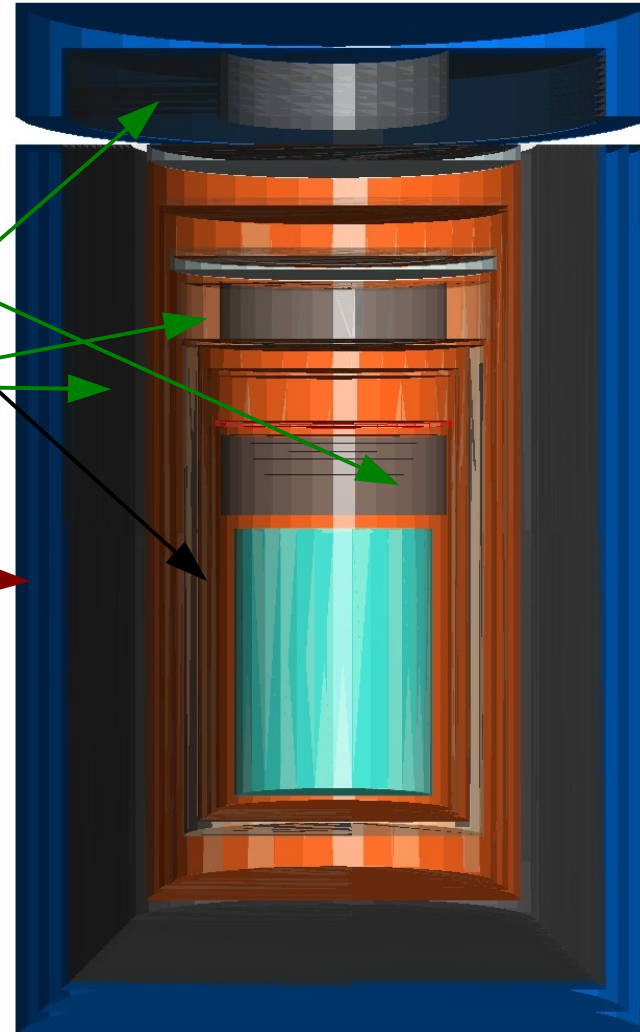
CUORE Shielding

CUORE will be Installed in a dilution refrigerator shields:

- 6 cm **Roman Pb** inner shield on the side ($<4\text{mBq/kg } ^{210}\text{Pb}$)
- 35 cm **Pb** inner shield on top ($16\pm4 \text{ Bq/kg } ^{210}\text{Pb}$)
- 25 cm **Pb** external shield ($16\pm4 \text{ Bq/kg } ^{210}\text{Pb}$)
- Neutron shield:
18 cm **Borated(10 %)-polyethylene**
- Anti-radon box: **nitrogen overpressure**

Other geometries simulated

- internal shield: 3cmCu+ 3m Roman Pb
- different Boron concentration in n-shield
- borated Polyethylene internal to Pb shields



FLUKA vs GEANT



- **Studies and comparisons in literature:**

Araujo et al. hep-ex/0411026

Wang et al. hep-ex/0101049

Kudryavtsev, Spooner, McMillan hep-ex/0303007

Mei, Hime astro-ph /0512125

Wulandari et al, hep-ex/ 0401032

- **Different neutrons productions for em and had cascades in GEANT4 and FLUKA**

- **Muon spallation in GEANT4 disagree with experimental results**

- **In Pb: a factor 2 less neutrons in GEANT4**

Neutron production material dependent: $\langle n \rangle \sim A^{0.81}$

Neutron production muon energy dependent: $\langle n \rangle \sim E_{\mu}^{0.75}$

Poor data in Pb, reasonable agreement except Bergamasco (a factor ~3 less in MC)

- ♦ **Use FLUKA to compute neutron energy spectrum**

- ♦ **Use this spectrum as input for GEANT4 for the CUORE DBD background estimate**

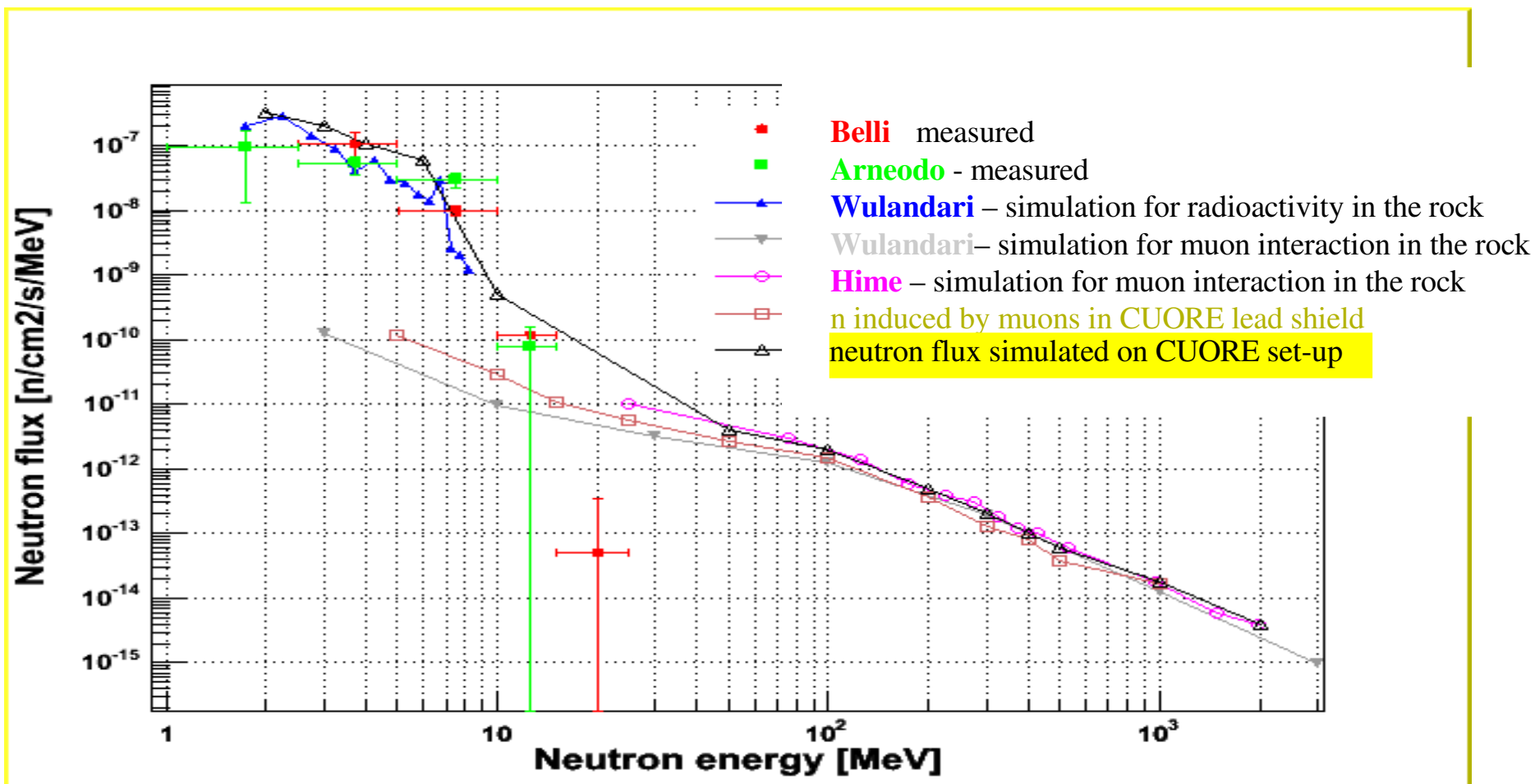
- **Measurements with neutron source for MonteCarlo validation(..up to 10 MeV)**

External Neutrons sources

- **(α, n) reactions** from **U** and **Th** contaminations and **spontaneous ^{238}U fission** in **rock, concrete, setup-materials** ($E_n < 10\text{MeV}$)

- **Muon-induced neutrons in rock:**

0.1% of neutrons from local radioactivity but **hard to shield**, very energetic neutrons (up to several GeV) can travel far from the μ track before being **thermalized and captured**.



Muons generation

- Muon flux measured by **MACRO** experiment (Hall B) as a function of polar (18° per bin) and azimuthal ($\sim 10^\circ$ per bin) angle
- **Angular distribution:** generate uniform flux inside a 5 m radius sphere and use **MACRO** maps (hit or miss technique) to tailor **underground muon flux**
- **Energy spectrum:** parametrized from ground level flux (well know) and transported underground taking into account, **for each given direction**, amount and shape of overburden rock

Thanks to
G Battistoni

Muon generated with underground energy: $E < 2000 \text{ GeV}$

- **Used muon flux:** $\Phi = (3.2 \pm 0.2) \cdot 10^{-4} \mu/\text{s}/\text{m}^2$

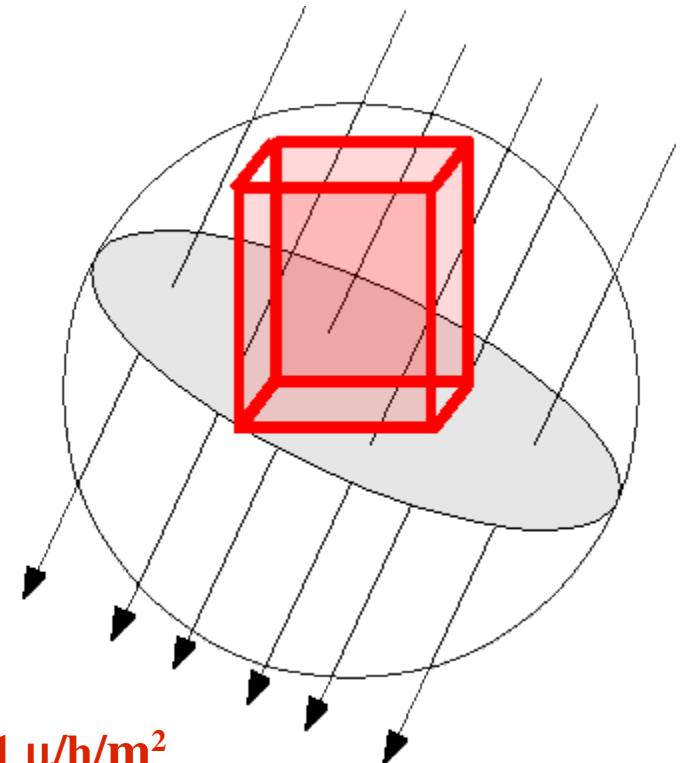
M. Cribier et al. (Gallex Col.)

Astron. Part. Phys. 6, 129 1997

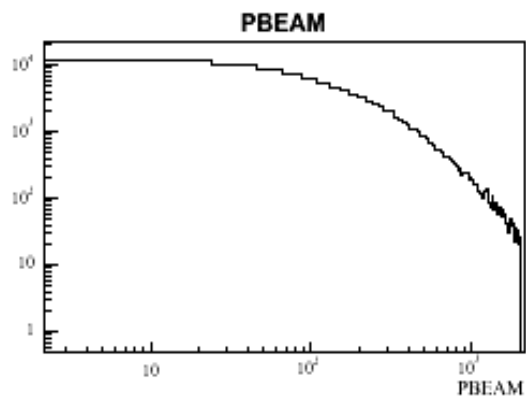
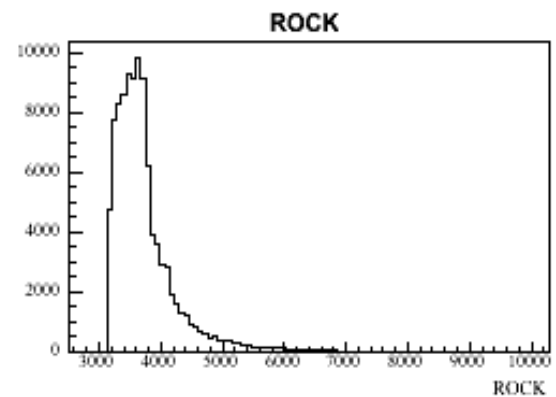
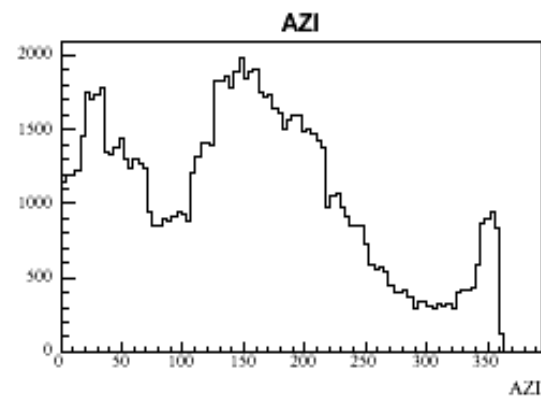
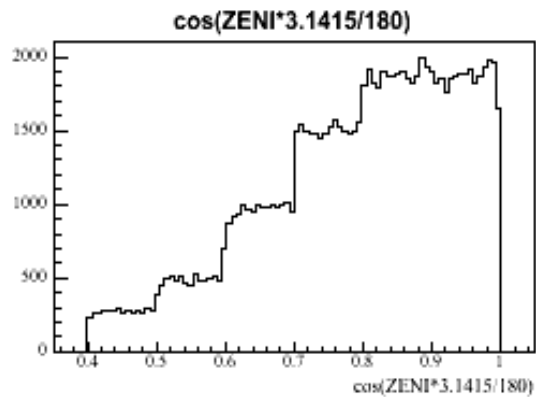
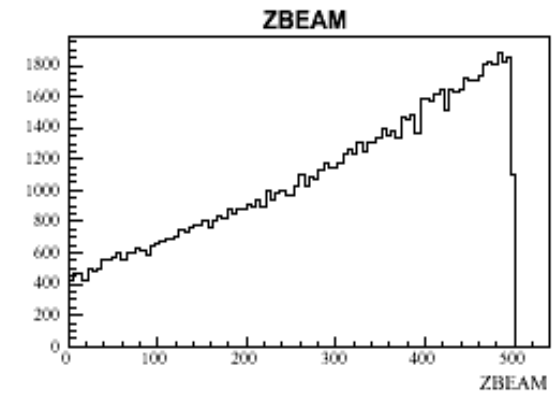
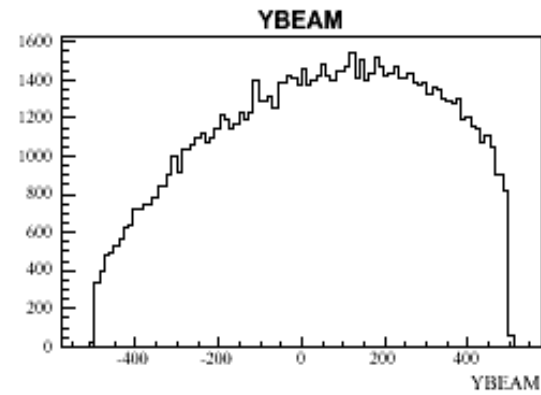
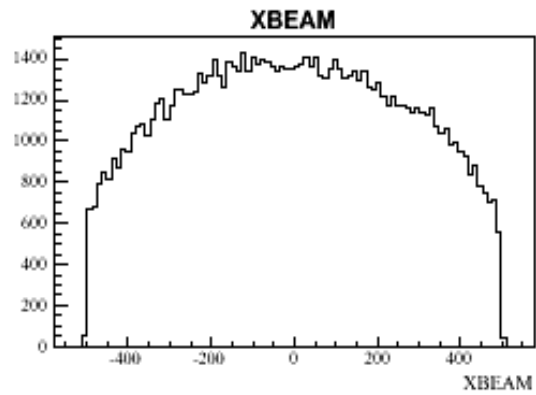
note: this is the highest in literature

◆ *Mei, Hime astro-ph /0512125 :* $\Phi = (2.58 \pm 0.3) \cdot 10^{-4} \mu/\text{s}/\text{m}^2$

◆ *Wulandari et al, hep-ex 0401032:* $\Phi = (2.78 \pm 0.2) \cdot 10^{-4} \mu/\text{s}/\text{m}^2 \sim 1 \mu/\text{h}/\text{m}^2$



Muon distributions



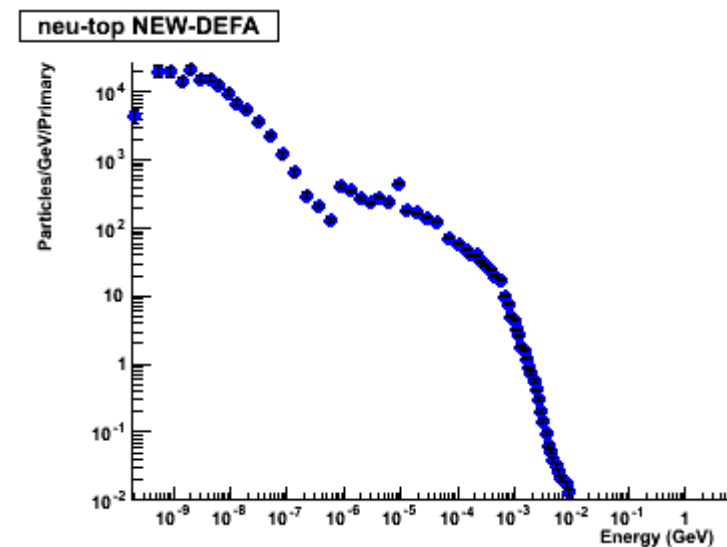
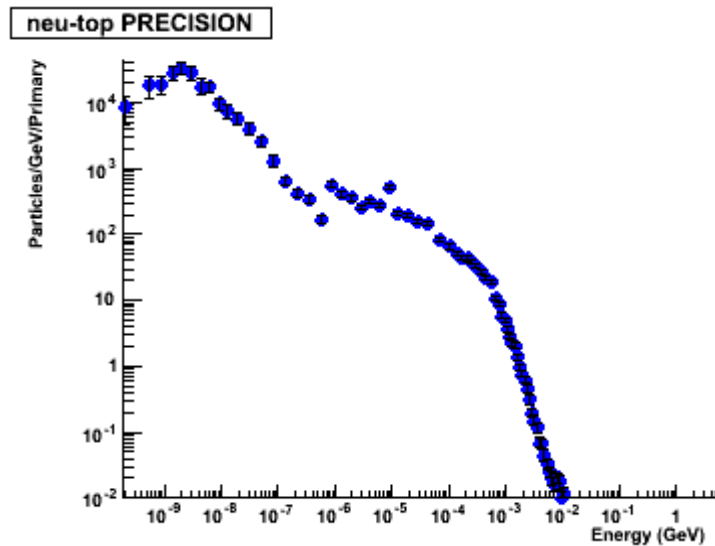
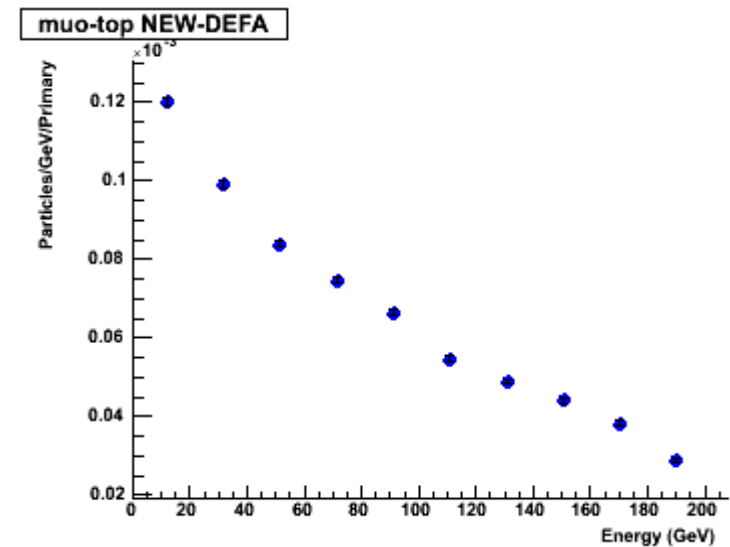
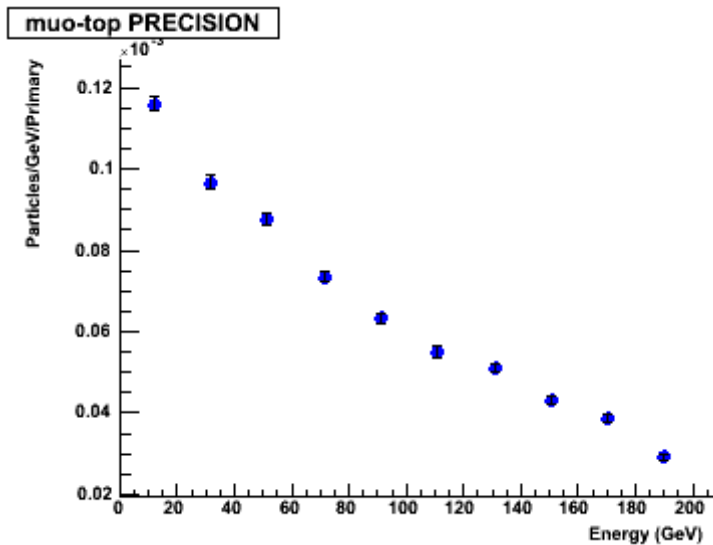
Thanks to
G Battistoni

Fluka Physics Cards



transport
Precision card
fully analogue

New-Default card
biased neutron (8 times faster)



Muon-induced neutron flux on detector

“Extreme” configuration:

ext shield:

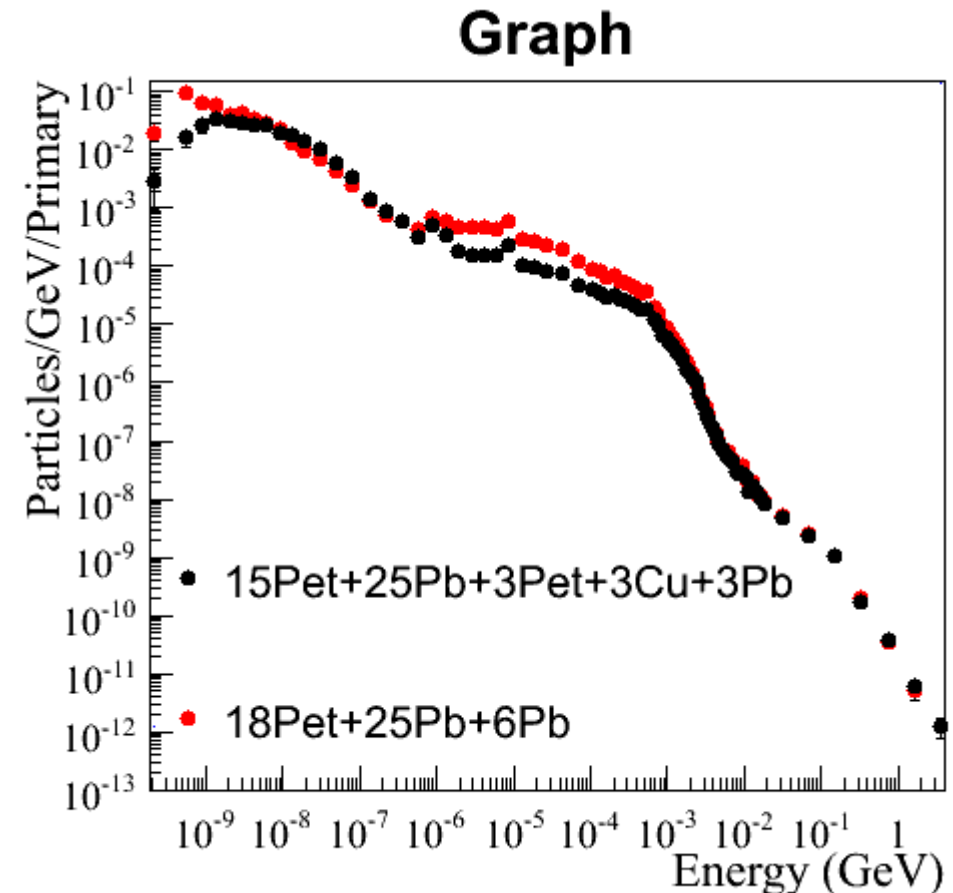
18 cm (1% B)n shield + 25 cm Pb

int shield: **6 cm Roman Pb**

ext shield:

15cm (10% B) +25 cm Pb + 3cm (10% B)

int shield: **3cm Cu + 6 Roman Pb**



$$\Phi = (57.7 \pm 3.6) \cdot 10^{-9} \text{ n/s/cm}^2$$

$$\Phi = (29.4 \pm 1.9) \cdot 10^{-9} \text{ n/s/cm}^2$$

Environmental neutron flux contribution: 1 order of magnitude less

$$\Phi = (7.6 \pm 0.7) \cdot 10^{-9} \text{ n/s/cm}^2$$

$$\Phi = (3.6 \pm 0.4) \cdot 10^{-9} \text{ n/s/cm}^2$$

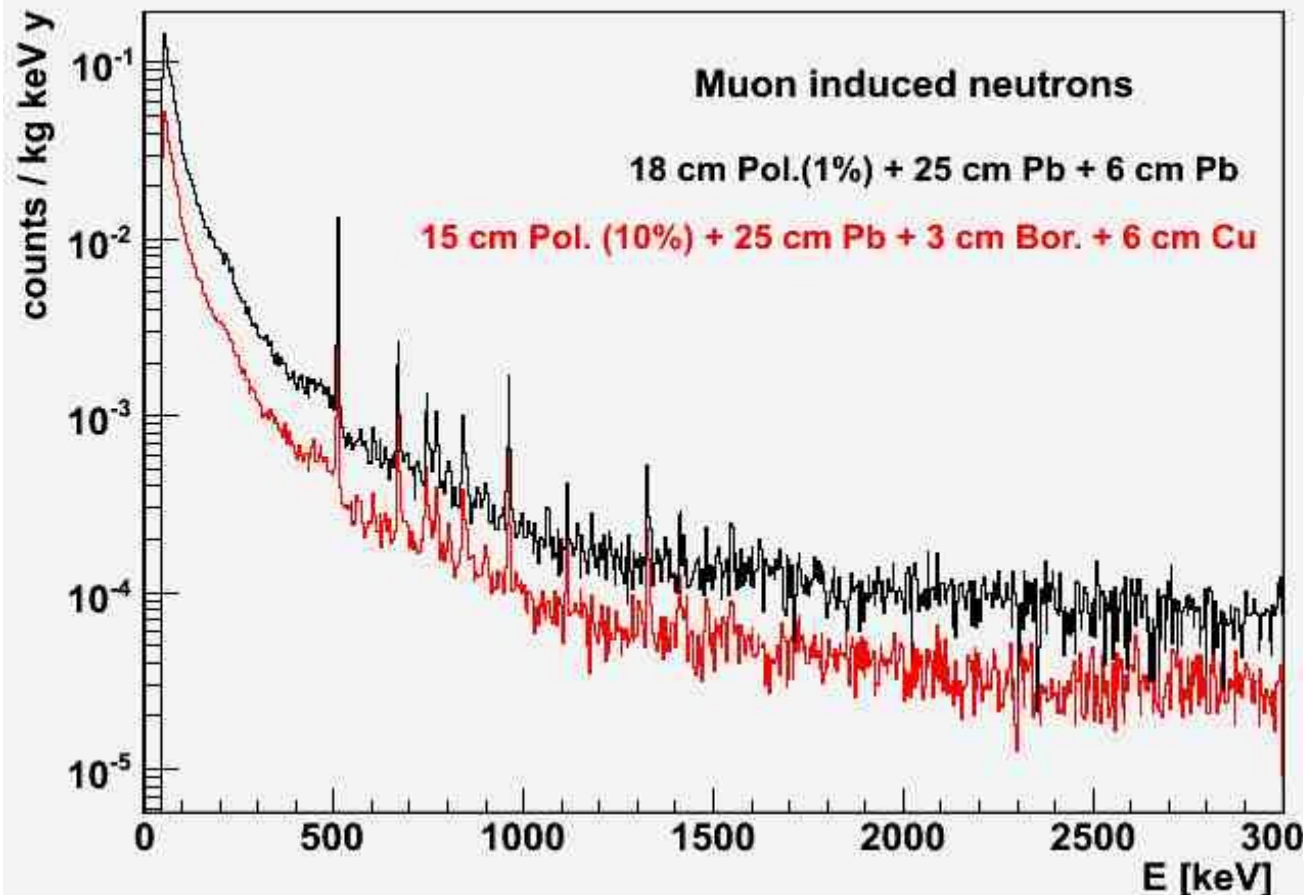
note: induced γ not included ...work in progress

Background in DBD region (GEANT4)



Preliminary results

Anti-coincidence spectrum



Anti-coincidence bkg:
(FWHM:5keV, ROI: 5σ around
2530 keV, 10 ms)

$(1.5 \pm 0.3) \cdot 10^{-4}$ counts/keV/y/kg
 $(5.6 \pm 1.2) \cdot 10^{-5}$ counts/keV/y/kg

Total bkg:
 $(2.4 \pm 0.2) \cdot 10^{-3}$ counts/keV/y/kg
 $(9.8 \pm 0.8) \cdot 10^{-4}$ counts/keV/y/kg

Environmental neutron flux contribution: one order of magnitude less

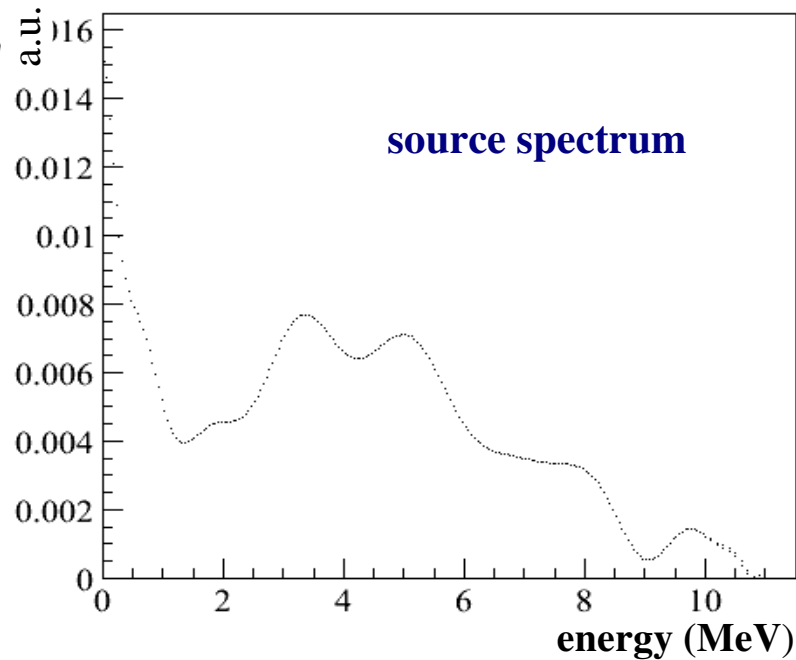
note: induced γ not included ...work in progress

Measurement with neutron source

Am-Be source: ~2200 n/s

hall C shielding:

10 cm Pb + 7cmPet+2cmCB₄+10cm Pb



4 different measurements

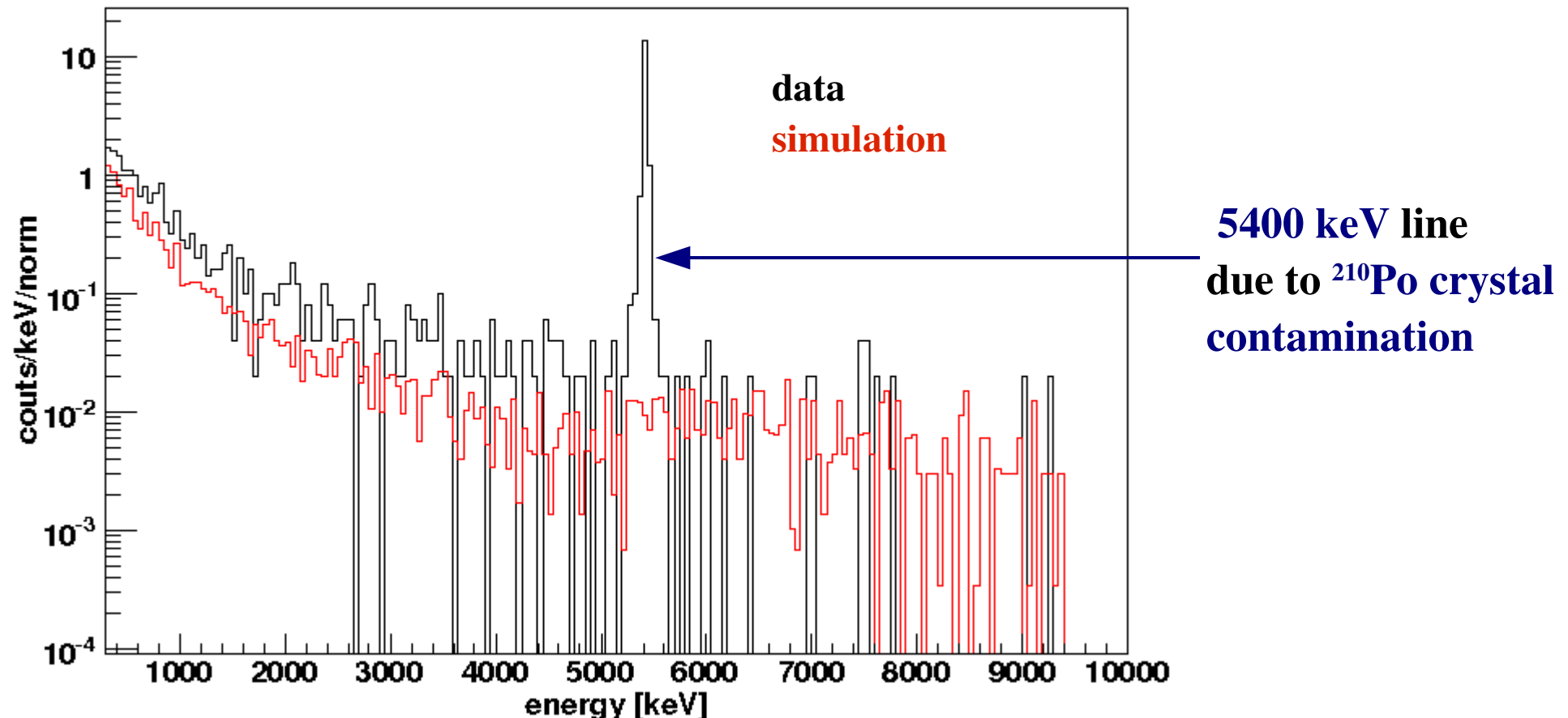
- standard set-up
- source in a 30 cm PET box
- without internal n-shield and different source position



Measurement with neutron source

Preliminary results

configuration:
source in 30 cm PET box



Simulation seem to underestimate neutron flux

n and muon-induced neutron not included -> minor contribution expected

γ background



External radiation: $\Phi = 7.7 \cdot 10^6 \gamma/\text{d}/\text{cm}^2$ measured with Ge detector and used as input for GEANT

$\text{bkg} = 1.5 \cdot 10^{-5} \text{ counts/kg/keV/y}$ with 24 cm external Pb shield

- ♦ Cryostat ^{232}Th bulk contamination contribution reduced by properly shielding in CUORE cryostat + selection of construction material

$\text{bkg} = < 10^{-3} \text{ c/keV/kg/y}$

- ♦ External Pb shield contamination: $100 \mu\text{Bq/kg}$

$\text{bkg} = 2.4 \cdot 10^{-4} \text{ counts/kg/keV/y}$

- ♦ Internal shield

- Roman lead contamination (6cm Pb):

$60 \pm 17 \mu\text{Bq/kg}$ $\text{bkg} = 6 \cdot 10^{-3} \text{ counts/keV/y/kg}$

$< 71 \mu\text{Bq/kg}$ $\text{bkg} < 7 \cdot 10^{-3} \text{ counts/keV/y/kg}$

need to measure
again?

- DownRun Pb

$< 22 \mu\text{Bq/kg}$ $\text{bkg} < 2 \cdot 10^{-3} \text{ counts/keV/y/kg}$

(but ^{60}Co contamination & 27 Bq/kg ^{210}Pb)

- Cu shield contamination : $< 12 \mu\text{Bq}$

$\text{bkg} < 2.4 \cdot 10^{-3} \text{ counts/keV/y/kg}$

(better for Th contamination.. worse for ^{60}Co contamination and neutron activation)

CUORE background estimate



source	10-3 counts/keV/y/kg
external gamma	<1
external apparatus	<1
detector structure bulk	<1
crystal bulk	<0.1
detector surfaces	~20-40
crystal surfaces	<3
neutrons	~0.01
muon induced neutrons	~0.1

→ The limiting factor up to now

Next Steps



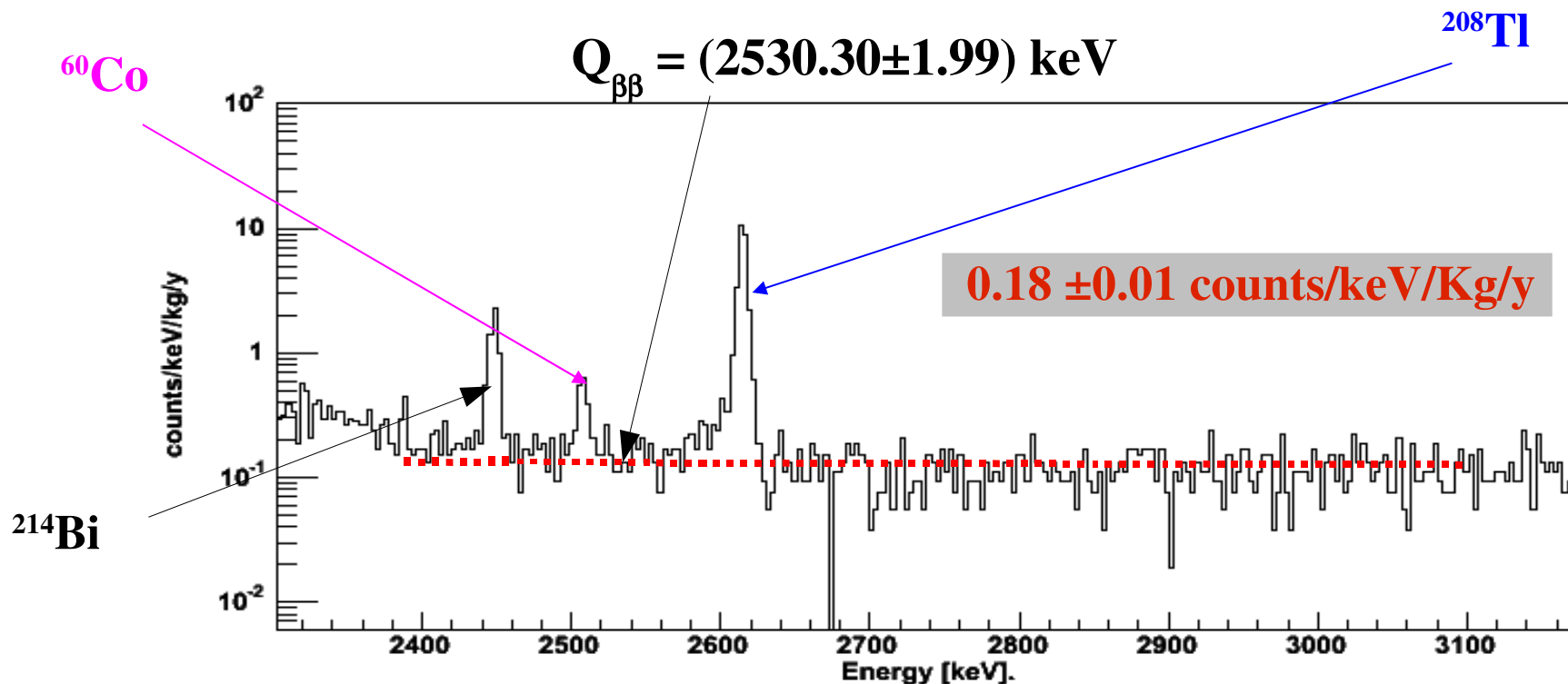
- **Double check simulation and add statistics**
- **Validate simulation with neutron source**
- **Include Isotope activation**
- **Include muon background and gamma induced background**
- **Evaluate background also in dark matter region**
- **Understand correlation with muons &
study veto system for muons tagging**
- **Publish results soon**

Cuoricino bkg knowledge



♦ In $0\nu\beta\beta$ region:

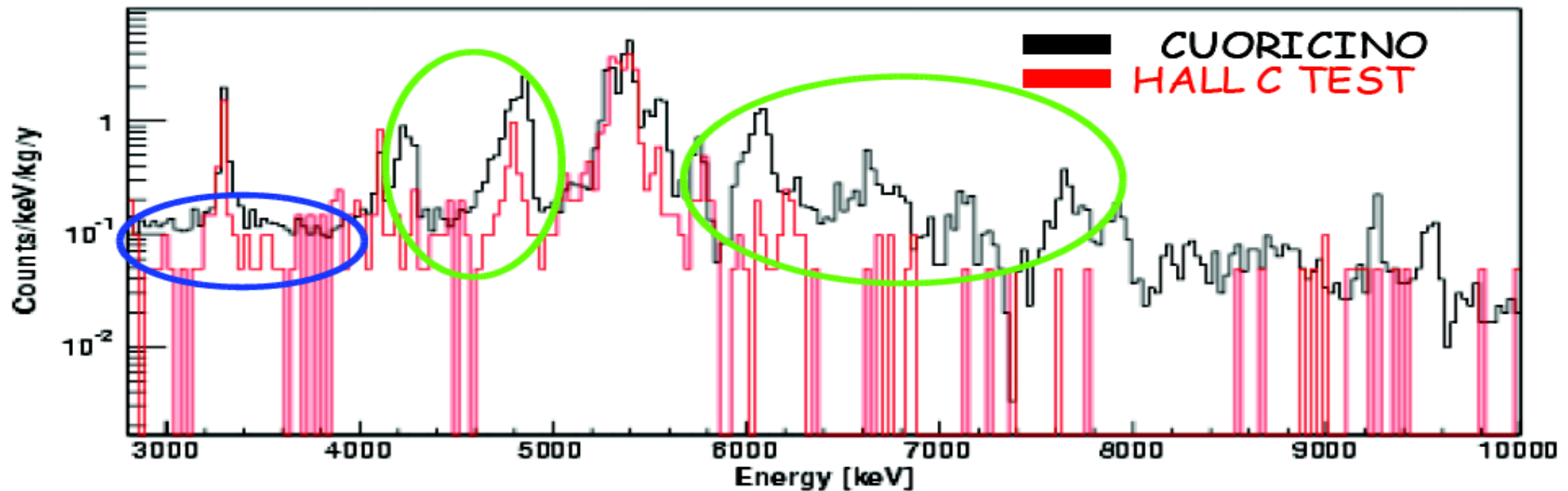
- $30 \pm 10\%$ ^{208}Tl (2614.5 keV line) via multi-Compton events from ^{232}Th in *cryostat shields*
- $10 \pm 5\%$ from crystals surface ^{238}U and ^{232}Th contamination
- $50 \pm 20\%$ from degraded α produced by ^{238}U and ^{232}Th contaminations of *mounting structure*
main candidate the *copper surface*
- negligible contribution from 2505 (1173 γ +1332 γ) keV ^{60}Co tail due *Cu cosmogenic activation*



Background reduction

◆ Surface contribution:

- test with new crystals surface cleaning (etching, lapping with $2\mu\text{m}$ SiO_2 clean powder)
reduction of a factor 4
- test with new Cu cleaning (etching, electro-polishing, passivation) and complete coverage of Cu facing the crystal with $\sim 50\mu\text{m}$ PET film
reduction of $\sim 40\%$ of flat continuum background



The extrapolated contribution to CUORE are

- ◆ Crystal Surface contamination contribution $< 3 \cdot 10^{-3}$ counts/kg/keV/y
- ◆ Copper Surface contamination contribution $< 5 \cdot 10^{-2}$ counts/kg/keV/y
- ◆ New structure with reduced Cu amount is being tested right now
- MC simulation Cu contribution $< 2.5 \cdot 10^{-2}$ counts/kg/keV/y

Muon-induced neutrons

Muon-induced neutrons in shields (mainly in Pb, $\langle n \rangle \sim A^{0.81}$)

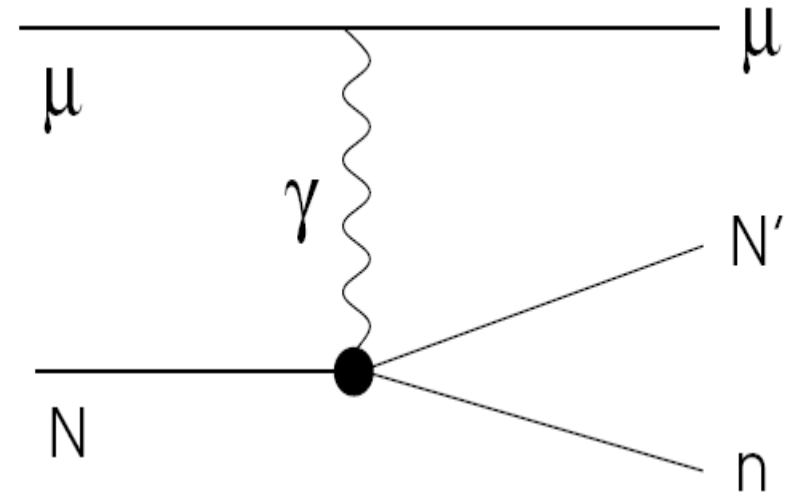
Not shielded, can be tagged by a muon veto

- **Muon energy spectrum underground:** from simulation or measured

- **Material geometry and composition** ($\sigma_{\mu}^{\text{em}} \sim Z^2/A$, $\sigma_{\mu}^{\text{had}} \sim A^{0.76}$)

- **Physical process**

- ◆ μ spallation,
- ◆ μ elastic scattering with bound n,
- ◆ μ induced em cascades,
- ◆ μ induced hadronic cascades,
- ◆ negative μ capture,
- ◆ secondary neutron production



Neutron production material dependent $\langle n \rangle \sim A^{0.81}$

Neutron production muon energy dependent $\langle n \rangle \sim E_{\mu}^{0.75}$

Mei, Hime

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astro-ph /0512125